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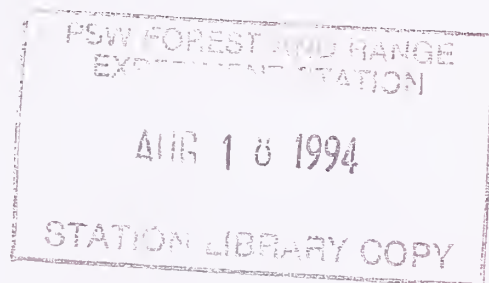**Rocky Mountain
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Experiment Station**

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**Research Paper
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Application of the MAGIC Model to the Glacier Lakes Catchments

John O. Reuss

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The MAGIC model (Cosby et al. 1985, 1986) was calibrated for East and West Glacier Lakes, two adjacent high-altitude (3200 m–3700 m) catchments in the Medicine Bow National Forest of southern Wyoming. This model uses catchment characteristics including weathering rates, soil chemical characteristics, hydrological parameters, and precipitation amounts and composition to calculate simulated lake and stream chemistry.

The simulations suggest that if precipitation were acidified to pH 4.27 with sulfuric acid, the ANC of the lakes would rapidly drop by about 30 meq/m^3. This rapid drop would be followed by a further slow decline. Assuming precipitation pH of 4.27, only West Glacier Lake dropped to an average annual ANC less than 0 or a pH of less than 5.6 within a 100-year simulation. However, at this level of precipitation acidity, very acid conditions could be expected on a seasonal basis. If the precipitation pH were lowered to 4.5, monthly average ANC values likely would not fall below 0, but shorter-term acid events might well occur.

The model could only be calibrated to current soil pH when input parameters allowed for at least 60 meq/m^3 of organic charge in the soil solution and when the aluminum solubility parameter was set for substantial undersaturation with respect to gibbsite. Important soil chemical characteristics can, therefore, be inferred by the use of such a model.

Keywords: acid precipitation, catchment, MAGIC model, stream chemistry

Application of the MAGIC Model to the Glacier Lakes Catchments

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Application of the MAGIC Model to the Glacier Lakes Catchments

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MANAGEMENT IMPLICATIONS

The susceptibility of two adjacent high-altitude catchments in the Medicine Bow National Forest of southern Wyoming to acidification by acid deposition was simulated using the MAGIC model. These catchments are similar in character to many found in wilderness areas in the Rocky Mountains. The simulations suggest that if precipitation were acidified to pH 4.27 with sulfuric acid, the acid neutralizing capacity of the lakes would rapidly drop by about 30 meq/m³. This rapid drop would be followed by a further slow decline. Within a 100–year simulation only one of the lakes (present acid neutralizing capacity [ANC] of near 38 meq/m³) dropped to an average annual ANC of less than 0 or a pH of less than 5.6. However, at this level of precipitation acidity, very acidic conditions could be expected on a seasonal basis. If the precipitation pH were lowered to 4.5, monthly average ANC values likely would not fall below 0, but shorter-term acid events might well occur. The most sensitive aquatic component is undoubtedly the tributary streams, and these would most likely experience acidic episodes at precipitation pH values well above 4.6.

INTRODUCTION

This report describes the application of the MAGIC model (Cosby et al. 1985, 1986) to two adjacent catchments at the Glacier Lakes Experimental Ecosystem Studies (GLEES) site in the Medicine Bow National Forest near Centennial, Wyoming. The model was used to examine the effect of possible future changes in precipitation chemistry on the chemistry of lake water.

This model can be run in either long-term or seasonal modes. Long-term simulations were run for both the East Glacier and West Glacier catchments. In the long-term mode the model is calibrated by entering present precipitation, hydrological, and soil parameters in order to match simulated and observed values of lake water chemistry. Forecasts may then be run assuming either a continuation of present conditions or changes that may be imposed in the future. The seasonal mode operates in a similar manner, except that some input parameters are entered on a monthly basis, and the calibration involves matching lake chemistry to both long-term and present seasonal chemistry. Seasonal simulations were run only for the West Glacier catchment.

This report describes the parameterization for both seasonal and long-term simulations while examining the predicted effects on lake chemistry and soil base saturation for various acidic precipitation scenarios.

LONG-TERM SIMULATIONS

Input Parameters

Many of the input parameters are taken from a previous report (Reuss et al. 1993) summarizing biogeochemical fluxes as observed at the GLEES site from 1988 through 1990. The summary in this paper is the source of most input parameters related to hydrology and water chemistry.

The ultimate source of the soils data is the report by Hopper and Walthall (1987). However, this raw data required a great deal of aggregation prior to use in the model. This aggregation is described in detail in Appendix A.

Hydrological Parameters

Hydrological and lake input parameters are shown in table 1. Two sets of simulation parameters are shown for West Glacier because the input parameters were revised after the initial runs were complete. This will be discussed later in more detail.

The overland flow parameter (F1) is set to zero for both catchments. In the MAGIC model overland flow is routed to the lake with no change in chemical composition. While in these catchments there is

Table 1.—Hydrology and surface water parameters for long-term simulations of East and West Glacier Lake catchments using the MAGIC model.

Parameter	Units	East Glacier	West Glacier (initial)	West Glacier (final)
Mean annual precip	m	1.07	1.99	1.99
Mean annual runoff	m	0.67	1.59	1.59
F1 (overland flow)		0.0	0.0	0.0
F2 (soil type 2)	%	81	39	39
F3 (soil type 2 drainage to surface water)	%	20	75	75
Lake retention time	yr	.21	.05	.05
Area (relative)	Frac	.10	.05	.05
Log10(KALOH3)		9.20	9.20	9.20
PK1 ORG		4.20	4.20	4.20
PK2 ORG		6.00	6.00	6.00
PK3 ORG		9.00	9.00	9.00
PK ALORG		0.00	0.00	0.00
PK ALHORG		0.00	0.00	0.00
Temp	°C	10.0	10.0	10.0
PCO2	atm	.0003	.0003	.0003
Total ORG	mmol/m³	5.0	5.0	5.0

undoubtedly flow on or near the soil or rock surfaces at snowmelt, available evidence suggests that even surface interaction with the soil rapidly changes the chemical composition of meltwater. Therefore, it seems inappropriate to treat this as surface flow in the model.

The model allows for two soils, either one above the other or side by side. For purposes of these runs, Soil 1 is the bare rock and rubbleland, while Soil 2 is an aggregation of all the true soils. The percentage of area which is bare rock or rubbleland (F2) comes from Appendix A. The percentage of flow from this rubbleland that goes directly to the surface water (F3) is purely an estimate. For East Glacier Lake it is taken as zero because there is a low percentage of rubbleland area in this catchment and it is generally found on the high land away from the lake. The West Glacier catchment is over 60% rock and rubbleland and much of this feeds into the tributary streams with little or no interaction with soil. Therefore, the F3 parameter has been set at 75% for West Glacier. The aluminum solubility $(\log_{10}(KAlOH_3))$ for each lake is set at 9.2, which corresponds to a solubility between that of synthetic gibbsite and amorphous $AlOH_3$. It is not a crucial parameter for our purposes.

The 4.91 version of MAGIC simulates organic acid in soils and water using a triproteric acid analog. Defining the dissociation requires three pK values, which have been set to 4.2, 6.0, and 9.0, respectively. Total organic (Total Org) was set at 5.0 meq/m³ for East and West Glacier. If completely dissociated there would be 3.0 mmol of negative charge for each mmol of total organic acid. The model also allows simulation of organo-aluminum complexes. This capability was not used so PK ALORG and PK ALHORG⁺ are set to zero.

The lake CO_2 partial pressure was set to 0.0003 atm, which is near the standard value. This simply means that the pH values calculated for each lake would be the pH measured after equilibration with air at 0.0003 atm CO_2. Mean annual lake temperature was set at 10 °C. Again, small variations in this parameter would have a minimal effect on the output.

Precipitation Chemistry

Precipitation chemistry data (table 2) are taken from Reuss et al. (1993). These are the 3-year means using the snow chemistry values as modified by NADP (National Atmospheric Deposition Program 1990) wet deposition values for the summer months (June–September). Values calculated in this manner differ somewhat from means calculated strictly from NADP data, particularly the 9.5 meq/m³ for SO_4, which would be 14.8 meq/m³ if only wet deposition data were used. The selection was based on the fact that mass balance indicates that if the NADP values are correct, then the West Glacier catchment is accumulating SO_4, while the snow data indicates a

Table 2.—Precipitation chemistry used as input for calibration of long-term simulations of the East and West Glacier Lakes catchments.

Parameter	meq/m³	Parameter	meq/m³
Ca	9.0	SO₄	9.5
Mg	2.2	Cl	2.5
Na	2.8	NO₃	10.1
K	1.2	F	0.1
NH₄	4.2		
pH	5.39		

Dry deposition factor is 1.2 for all components.

small source of SO_4 in the catchment. As some sulfur-bearing minerals have been identified in the West Glacier catchment (James Drever, University of Wyoming, pers. comm.), the latter case is deemed more likely. It is not a major factor, however, as the difference is small compared to the precipitation SO_4 levels imposed in the forecast scenarios. A dry deposition factor of 1.2, i.e., total deposition 1.2 times wet deposition, was imposed for all components of precipitation. This may be a bit high considering that dry deposition for much of the year would be included in the snow. However, the snow samples were from open areas, and there are forested areas in both catchments that would trap aerosols. While in most cases the presumed dry deposition amounts are small, they can be significant when applied to SO_4 in the forecast scenario. Thus, in a forecast scenario that increases wet SO_4 from 9.5 to 60 meq/m³, we are increasing total SO_4 loading from 11.4 to 72 meq/m³.

Soil Parameters

Soil parameters used for the calibration runs are listed in table 3. Soil depths and bulk densities are not those found in the catchments. However, for the actual soil (Soil 2), the product of bulk density times soil depth (i.e., the soil mass in kg/m²) is the observed value for the aggregated soil (Appendix A). This modification is simply a modeling convenience used to ensure a favorable relationship between hydraulic residence time and internal time steps for efficient and accurate integration. The rock and rubbleland is represented as Soil 1, another modeling convenience that allows simulation of weathering in these areas and the transport of weathering products to either the soil areas or lake. Soil 1 is assumed to have a very low-bulk density (2 kg/m³) so that it quickly comes to an equilibrium pH dictated by the rainfall composition and the rate of weathering.

Cation exchange capacities (CEC) are observed values. The soil is assumed to adsorb little or no SO_4, and the adsorption parameters are set to arbitrary values that result in little or no sulfate retention. This assumption is based on the observation that the SO_4 values vary over the season at the lake outlets,

Parameter	East Glacier Soil 1	Soil 2	(Initial) West Glacier Soil 1	Soil 2	(Final) West Glacier Soil 1	Soil 2
Soil depth (m)	1.00	1.00	1.00	1.00	1.00	1.00
Porosity (Frac)	0.40	0.40	0.40	0.40	0.40	0.40
Bulk density (kg/m^3)	2	520	2	489	2	489
CEC (meq/kg)	121	121	120	120	120	
SO_4 Halfsat (meq/m^3)	10	10	10	10	10	10
SO_4 Maxcap (meq/kg)	1.0	1.0	1.0	1.0	1.0	1.0
$Log10(KAlOH_3)$	8.10	6.50	8.10	6.00	8.10	6.20
$Log10(KS_{AlCa})$*	3.66	1.42	3.70	1.38	1.50	1.55
$Log10(KS_{AlMg})$*	3.85	1.44	3.88	1.56	1.54	1.78
$Log10(KS_{AlNa})$*	−0.11	−0.52	0.59	−0.57	−0.65	−0.38
$Log10(KS_{AlK})$*	−1.64	−2.77	−1.34	−2.50	−2.55	−2.33
PK1 ORG	4.20	4.20	4.20	4.20	4.20	4.00
PK2 ORG	6.00	6.00	6.00	6.00	6.00	6.00
PK3 ORG	9.00	9.00	9.00	9.00	9.00	9.00
PK ALORG	0.00	0.00	0.00	0.00	0.00	0.00
PK ALHORG+	0.00	0.00	0.00	0.00	0.00	0.00
Temp (°C)	8.0	8.0	8.0	8.0	8.0	8.0
PCO_2 (atm)	.0058	.0058	.0058	.0058	.0058	.0058
Total ORG ($mmol/m^3$)	20	110	5	110	5	110
Initial exch. (%)						
Ca	31.2	31.2	33.3	33.3	33.3	33.3
Mg	11.6	11.6	11.5	11.5	11.5	11.5
Na	0.3	0.3	0.3	0.3	0.3	0.3
K	0.5	0.5	0.6	0.6	0.6	0.6
Weathering (meq/m^2)						
Ca	20.7	20.7	40.0	40.0	20.0	70.0
Mg	9.3	9.3	19.0	19.0	9.5	33.3
Na	3.8	3.8	7.4	7.4	3.7	13.0
K	0.5	0.5	2.9	2.9	1.5	5.0
SO_4	0.0	0.0	4.6	4.6	4.6	4.6
H^+ ion power**	0.5	0.5	0.5	0.5	0.5	0.5
Uptake						
NH_4 (meq/m^2)	6.2	6.2	9.2	9.2	9.2	9.2
NO_3	12.8	12.8	16.3	16.3	16.3	16.3

*Selection coefficients calculated internally.
** H^+ ion power applies to base cations only. Sulfur weathering assumed to be independent of H^+.

particularly at West Glacier where the variation is a factor of 2 or more. However, the assumption is still open to question and SO_4 adsorption in the catchment should probably be examined more critically.

The aluminum solubility parameter was initially set at 8.1, or approximately the solubility of synthetic gibbsite. However, the resulting soil pH values were higher than those observed, indicating that the soil must be undersaturated with respect to this solid phase, so these values were lowered as part of the calibration discussed below. The value of 8.1 was retained for Soil 1 (rock and rubbleland).

The selection coefficients are internally calculated in the model and will be discussed as part of the calibration procedure as will the pK(H) values for the organic matter. The initial runs were made using an earlier model version (4.01) that did not have the capability to simulate organo-aluminum complexes. Thus, pK values for organo-aluminum complexes are set to zero.

Annual average temperature was set at 8 °C for all runs. The optional internal calculation of PCO_2 as a function of temperature gives a value of 0.0058 atm, which is consistent with a limited amount of recent data, so this value was used in most cases. The soil is sufficiently acid so that the system is not particularly sensitive to CO_2. Organic acids, however, are a major anion in the soil; and while highly variable, calculation of a charge deficit for a limited number of soil solutions suggests that the organic charge is between 50 and 100 meq/m^3 (RMFRES, unpublished data). The concentration of negative charges in the system depends on both the Total Org and the pK values, but the combination of a Total Org value of 110 $mmol/m^3$ and the above pK values results in an appropriate level of organic charge. A small amount of total organics (5–20 $mmol/m^3$) is presumed to be present in the rock and rubbleland.

Weathering values are also shown in table 3. For the initial calculation of the weathering values it was assumed that the system is in steady state, so that the difference between the net flux from the catchment and the deposition inputs (adjusted for 20% dry deposition) represents weathering. These initial values resulted in a reasonably good match between simulated and observed water chemistry. To the extent that there may be some anthropogenic increase represented in present levels of SO_4 and NO_3, this might be an overestimate. Given the relatively low levels present in the precipitation, any error from this source will be small in relation to the deposition levels imposed in the forecast scenarios. Furthermore, the assumption is conservative in the sense that if current inputs of the strong acid-forming anions actually do represent an increase over background, the weathering rates calculated in this manner would be greater than the true rate. A fractional-order (0.5) weathering rate dependence on H^+ has been assumed, except for sulfur weathering which is assumed to be independent of H^+.

The steady state assumption requires that the total amount of nitrogen in the catchment be constant, but net flux data shows that there is less NO_3 and NH_4 in the surface water discharge than is input in precipitation. One explanation is gaseous loss of N from the system, while another is incorporation in slow-turnover organic compounds (not strictly steady state). At any rate there is clearly a loss or immobilization of N in the system. The MAGIC model simulates any such sink as uptake. Thus, the uptake values for NO_3 and NH_4 simply represent the observed differences between input and outflow.

Model Calibrations

The steady state assumption requires that neither soil nor lake chemistry change over time when present levels of inputs are maintained. Furthermore, neither soil solution nor lake chemical parameters are input. Thus, given the hydrological inputs, pre-

cipitation chemistry, and current soil base status, the calibration procedure involves adjusting certain parameters for which we do not have definitive input data in a manner that will result in simulation of current lake chemistry without a change in base saturation over time. The major parameters adjusted in this process are the solubility of aluminum compounds in the soil (KALOH3), and the parameters that relate to the total number of organic charges and their dissociation. The selection coefficients that control the exchange of cations between the soil exchange and solution phases, calculated internally in the model, are also important factors in model calibration.

The modeling process involves a preliminary run using trial values followed by parameter adjustment consistent with established principles of soil and water chemistry. Preliminary runs (data not shown) attained lake chemistry values that agreed reasonably well with observed values. However, the model pH of the soil (i.e., Soil 2) was approximately 5.0, which is well above the observed soil pH. Two causes for this discrepancy were identified. First, the preliminary value of the Al solubility constant (8.1) was not consistent with the observed soil pH of 4.5 or less due to the buffering by Al minerals that would occur if that value accurately represented the system. This observed pH implies undersaturation of Al with respect to synthetic gibbsite, which is simulated by reducing the value of this constant to values in the range of 6.0–6.5. Secondly, the preliminary Total Org value of 60 mmol/m^3, when used in conjunction with the assumed dissociation constant, did not provide sufficient negative charge to support the observed soil pH values. Charge balance calculations on a limited amount of soil solution data suggest that the actual organic charge should be in the range of 60–100 mols(-)/m$_3$, although it is highly variable in both space and time. Accordingly, the input value was increased to 110 mmol/m^3, which resulted in a net organic charge in the appropriate range. This could have been achieved equally well by adjusting the pK values.

Finally, an additional constraint was imposed by the author in that the log$_{10}$ of the Al-Ca selection coefficient was required to be in the range of 1.0–2.0. The MAGIC model calculates these coefficients internally, and given appropriate weathering rates, lake chemistry can be duplicated with almost any set of values for the parameters that control PCO$_2$, Al solubility, and organic charge. However, the result would also be widely varying values of the selectivity coefficients that control the exchange of ions between the exchange and solution phases in the soil. The author has examined this parameter for a number of soils (Reuss and Hopper, unpublished data), and has concluded that actual values for mineral soils are likely to be in the range of 0.0–2.0. The constraint of 1.0–2.0 is conservative in the sense that lower values tend to predict greater degradation of surface waters for a given level of acid inputs. For the parameter sets used, the Al-Ca selection coeffi-

cients (Soil 2) were in the range of 1.4–1.6. Calculated values of the selection coefficients for Soil 1 (bare rock) are irrelevant as there is virtually no cation exchange capacity.

The parameter sets obtained following these adjustments (tables 1–3) were judged to simulate the present system in a satisfactory manner and were then used for baseline runs. Output parameters for these baseline runs are shown in tables 4 and 5. Forecasts were then run in which changes in deposition were imposed on these baseline systems.

Table 4.—Present values of observed and simulated parameters for East Glacier Lake.

Parameter	Observed	Simulated
Lake (meq/m^3)		
Ca	46.4	44.9
Mg	17.6	16.7
Na	10.7	9.6
K	3.0	3.0
NH$_4$	0.3	0.8
H$^+$	0.1	0.1
SO$_4$	16.8	18.1
Cl	2.9	4.8
NO$_3$	0.6	2.0
H$_2$A$^-$	NA	0.6
HA^{2-}	NA	8.7
ANC	50.4	49.9
SBC	78.0	74.2
SAA	20.3	24.9
Soil pH	<4.5	4.6

Table 5.—Present values of observed and simulated parameters for West Glacier Lake.

Parameter	Observed	Simulated Initial	Simulated Revised
Lake (meq/m^3)			
Ca	37.7	37.3	37.0
Mg	15.1	14.6	14.5
Na	8.9	8.6	8.6
K	3.6	3.5	3.5
NH$_4$	0.5	0.8	0.8
H$^+$	0.1	0.2	0.2
SO$_4$	17.2	17.0	17.0
Cl	3.1	3.8	3.0
NO$_3$	4.9	5.0	5.5
H$_2$A$^-$	NA	0.8	0.8
HA^{2-}	NA	8.3	8.3
ANC	38.6	38.4	38.0
SBC	65.8	64.8	64.4
SAA	25.2	25.8	25.5
Soil pH	<4.5	4.5	4.5

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The reader will note that two baseline sets are reported for West Glacier. While the initial set results in a reasonable simulation of present conditions, a problem was encountered when these parameters were applied on a seasonal basis. At West Glacier, much of the input is to bare rock, which is simulated as Soil 1. Most of this input then moves directly to the lake via streams, with little or no interaction with soil. In the initial simulation, weathering rates were assumed to be the same for both Soil 1 (bare rock) and Soil 2. While this arrangement approximated the correct chemical composition in the lake, the simulated ANC of the water flowing directly from the bare rock (41 meq/m³) was approximately the same as the lake ANC. Data are available, however, showing that tributary streams from this area actually have much lower ANC, on the order of 6 to 9 meq/m³. The revised simulation represents decreased weathering rates for Soil 1, offset by an increase in weathering in Soil 2. A few other minor adjustments were also included. After modification the simulated lake chemistry remained very similar to the observed values (table 5). However, the ANC of the output from Soil 1 dropped to 19 meq/m³. While this value is still well above the observed value from the tributary streams, no further adjustments were made because the streams on which these measurements were made largely originate from the quartzite areas and do not reflect somewhat higher ANC values observed in waters from areas containing more mafic rocks (Rochette et al. 1988). No revised East Glacier runs were made because the proportion of bare rock is much lower in this catchment, and in this case the bare rock runoff is routed through the soil.

The fact that simulated lake chemistry, even for the preliminary runs, is very similar to the observed values is encouraging but does not necessarily verify the model, because the input weathering rates were calculated from the observed data. It simply confirms that the relevant assumptions in the model are similar to those used in the calculations.

Results

After calibration as described above, forecasts were run using varying deposition scenarios. The baseline or medium forecast scenario involved increasing wet SO_4 deposition to 60 meq/m³ which, when combined with a dry deposition factor of 1.2, results in a total SO_4 input of 72 meq/m³, compared to 11.4 meq/m³ for the simulation of present conditions. Additional scenarios include increasing wet SO_4 to 30 meq/m³ (36 meq/m³ total) and to 85 meq/m³ (102 meq/m³ total). This increased deposition was imposed linearly over a 5-year period and maintained as a level input thereafter.

East Glacier

Selected chemical values from the East Glacier simulations are shown in table 6 for both present values and the three forecast scenarios. These values are for 30 years after the initial increase in deposition and 25 years after the final level was attained. Lake ANC decreased about 0.65 meq/m³ for each meq/m³ increase in the acidity of the precipitation, or 0.55 meq/m³ increase when dry deposition is taken into account. After concentration of SO_4 by evapotranspiration, this translates to approximately a 0.35 meq/m³ decrease in lake ANC for each meq/m³ increase in lake SO_4. Thus, about 65% of deposition acidity is predicted to be neutralized by base cations from either weathering or exchange; i.e., Henriksen F values (Henriksen 1979, 1980; Wright 1983) range from 0.63 to 0.67.

Note that the simulation predicts that enhancement of weathering due to greater acidity of precipitation is much greater on the rock and rubbleland (Soil 1) than in the true soil (Soil 2). This is because the true soil buffers the increased H^+ ion inputs much more effectively than does the bare rock. As weathering is assumed to be proportional to the 0.5 power of H^+, simulated weathering increases more rapidly on the bare rock where the buffering is almost entirely due to weathering. At East Glacier, however, only about 19% of the area is rock and rubbleland; so on an overall basis, processes in the true soil predominate.

Table 6.—Selected chemical parameters from MAGIC simulations of the East Glacier Lake catchment. For the forecast scenarios, precipitation acidity was increased linearly from the present level over a 5-year period. Values shown are those predicted 25 years after precipitation acidity reached the final level.

Parameter	Units	Present	Forecast scenarios		
			Low	Medium	High
Precipitation					
SO_4 (wet)	meq/m³	9.0	35	60	85
SO_4 (wet+dry)	"	10.8	42	72	102
pH (approx)		5.39	4.55	4.27	4.11
Lake					
Ca	meq/m³	45	67	89	112
Mg	"	17	25	33	42
Na	"	10	11	11	12
K	"	3	4	4	4
SO_4	"	18	67	114	161
Cl	"	5	5	5	5
Al^{3+}	"	0.0	0.0	0.0	0.2
Alk	"	50	32	18	3
pH		6.8	6.6	6.2	5.5
F factor		0.63	0.67	0.67	
Soil 2					
Base Sat	%	43.6	42.8	41.8	40.8
pH		4.6	4.5	4.4	4.3
Weathering (Total base cations)					
Soil 1 (rock)					
meq/m²/yr		31	46	65	83
Soil 2	"	31	35	41	44

The time course of selected lake and soil parameters is shown in figures 1, 2, and 3. Most of the drop in lake ANC and pH occurs immediately upon onset of the increased deposition. This direct response probably results mostly from what is known as the salt effect, whereby an increase in soil solution concentration decreases pH as a result of exchange processes. Once deposition reaches the new input level, there is a very slow decline in lake ANC and pH. This delayed effect comes about because the rate of base cation depletion due to leaching now exceeds the weathering rate, and there is a depletion of base cations on the soil exchange. The soil is actually quite well-supplied with bases, so this depletion is slow. These results suggest that once the initial drop in pH and ANC occurs, the system is fairly well-protected against further loss in ANC by its capacity to supply exchangeable base cations. Only at the highest level of input does the predicted annual average pH of the lake drop below the neutral point of 5.6.
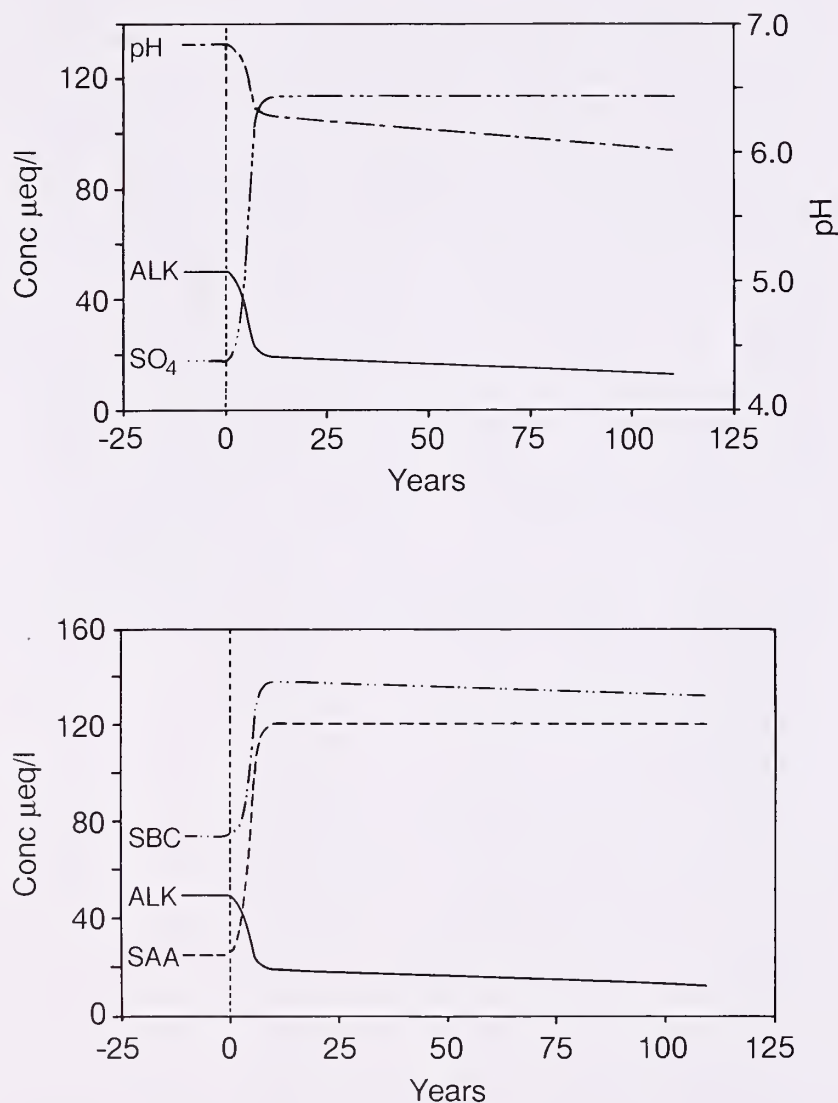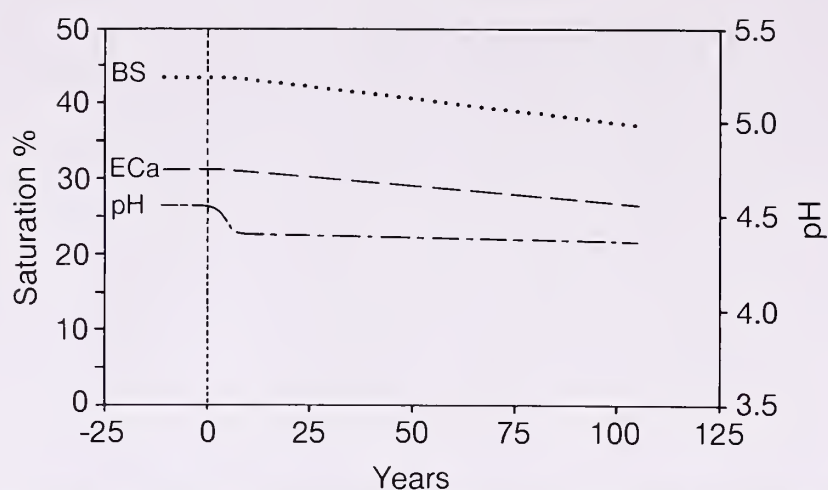

Figure 2.—Time course for soil base saturation (BS), exchangeable Ca (ECa), and pH from East Glacier simulations.
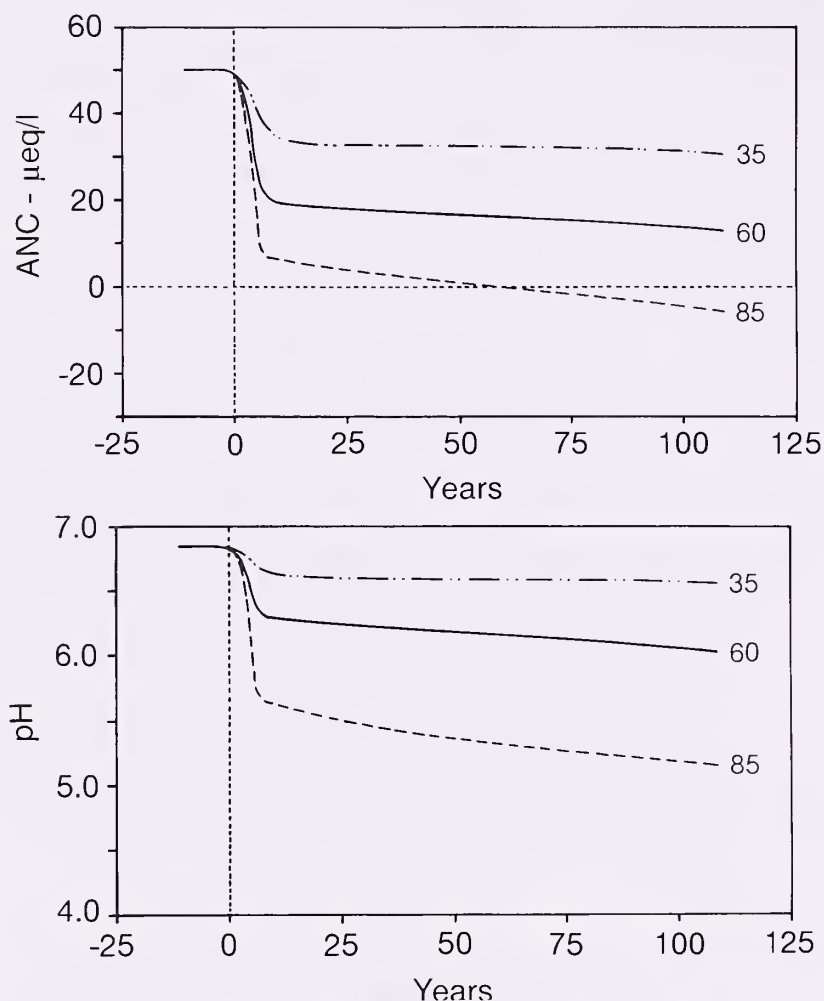
Figure 3.—Upper: ANC at East Glacier Lake outlet with wet deposition increasing to 35, 60, and 85 meq/m^3 over a 5-year period starting with year one. Lower: Time course for simulated pH.

West Glacier

Selected chemical parameters from the West Glacier simulations are shown in table 7. As the final set of input parameters were deemed to be the more accurate representation of the system, the low and high deposition forecast scenarios were applied only to this set. First, it should be noted that while the difference between East Glacier and West Glacier sulfate concentrations is small at present, the projected concentrations as a result of increased depo-

Figure 1.—Time course for East Glacier Lake outlet chemistry from baseline simulations. Precipitation SO$_4$ increased from 9.5 meq/m^3 to 60 meq/m^3 over a 5-year period starting with year one (precip pH approximately 4.3). Upper: ANC (ALK), pH, and SO$_4$. Lower: ANC, sum of base cations (SBC), and sum of strong acid anions (SAA).

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sition are lower for West Glacier than East Glacier. A simulated increase in total SO_4 deposition from 10.8 meq/m^3 of precipitation to 72 meq/m^3 results in a lake SO_4 concentration of 114 meq/m^3 in East Glacier, while a similar increase would likely result in 93 meq/m^3 SO_4 in West Glacier. This difference arises from the higher precipitation amounts and consequent lower relative concentration due to evapotranspiration at West Glacier. The decrease in lake ANC per unit increase in precipitation acidity (wet + dry) was about 0.6 meq/m^3, or slightly larger than the 0.55 meq/m^3 found for East Glacier. The greater loss of ANC per unit of precipitation acidity plus the fact that lake SO_4 changes less per unit of increased precipitation acidity results in lower Henriksen F values (0.49 to 0.53) at West Glacier.

Time course plots for these West Glacier simulations using the final input parameter set are shown in figures 4, 5, and 6. As at East Glacier, the major effect on lake chemistry shows up quickly. However, at West Glacier the subsequent drop in soil base saturation and lake ANC is somewhat more rapid than that observed in the East Glacier simulations, reflecting the lower fraction of the area covered by soil. The pH and ANC relationships in figure 6 are interesting in that after the initial drop, the slope of the pH curve is greater at 60 meq/m^3 wet deposition level than at either the 35 meq/m^3 or the 85 meq/m^3 level. This is because the curve for the 60 meq/m^3 passes through the bicarbonate equivalence point of zero ANC, where pH is much more sensitive to changes

in ANC than at either more positive or more negative ANC values. The flat pH curve for the high deposition also reflects aluminum buffering at pH values near 5.0 and below. Thirty years after onset of the high level of deposition the model predicts 7.5 meq/m^3 of Al^{3+} in West Glacier Lake (table 7).
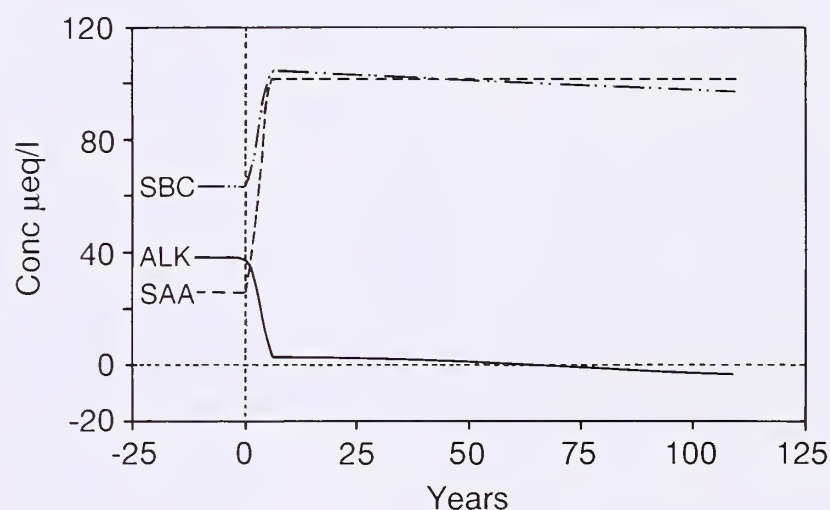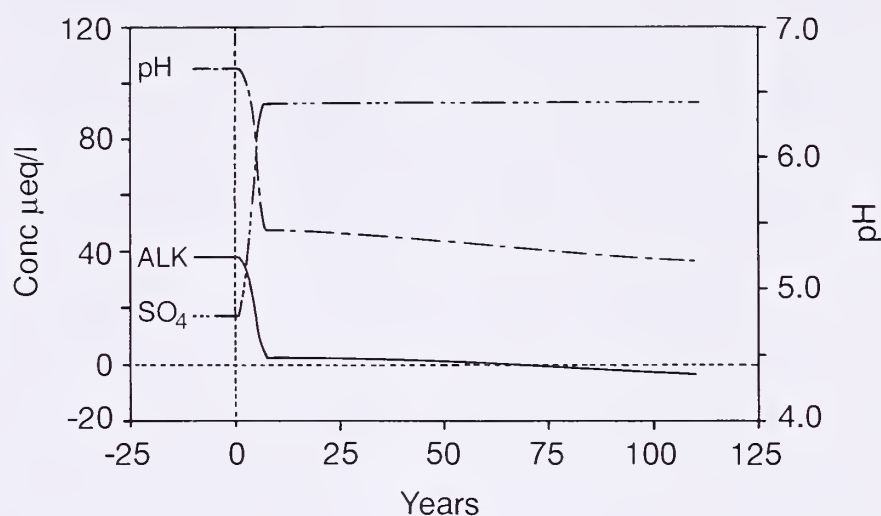
Figure 4.—Time course for West Glacier Lake outlet chemistry from baseline simulations using the final input parameters. Precipitation SO_4 increased from 9.5 meq/m^3 to 60 meq/m^3 over a 5-year period starting with year one (precip pH approximately 4.3). Upper: ANC (ALK), pH, and SO_4. Lower: ANC, sum of base cations (SBC), and sum of strong acid anions (SAA).
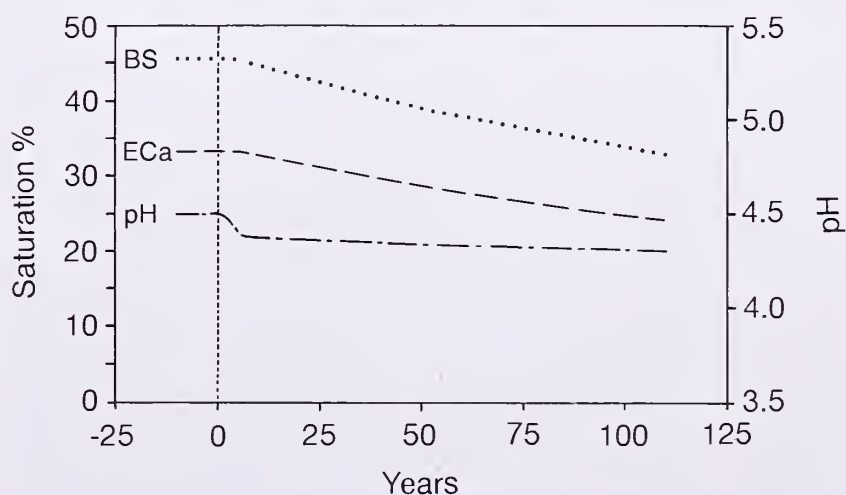
Figure 5.—Time course for soil base saturation (BS), exchangeable Ca (ECa), and pH from West Glacier simulations using the final input parameters.

Table 7.—Selected chemical parameters from MAGIC simulations of the West Glacier Lake catchment. For the forecast scenarios, precipitation acidity was increased linearly from the present level over a 5-year period. Values shown are those predicted 25 years after precipitation acidity reached the final level. The initial parameter set was run only for the medium deposition scenario.

| | Present | | Forecast scenarios | | | |
| | | | Medium | Low | Medium | High |
Parameter	(Init)	(Final)	(Init)	(Final)	(Final)	(Final)
Precipitation (meq/m^3)						
SO$_4$ (wet)	9.0	9.0	60	35	60	85
SO$_4$ (wet+dry)	10.8	10.8	72	42	72	102
pH (approx)	5.39	5.39	4.27	4.55	4.27	4.11
Lake (meq/m^3)						
Ca	37	37	64	49	62	74
Mg	15	15	26	20	25	30
Na	9	9	11	10	11	12
K	4	4	5	4	5	5
SO$_4$	17	17	93	55	93	130
Cl	4	4	4	4	4	4
Al^{3+}	0.0	0.0	0.1	0.0	0.3	7.5
Alk	38	38	6	20	2	−19
pH	6.7	6.7	5.6	6.3	5.4	5.0
F factor	0.58	0.53	0.52	0.49		
Soil 2						
Base sat %	45.6	45.2	42.2	43.8	41.7	39.5
pH	4.4	4.5	4.3	4.4	4.3	4.2
Weathering (Total base cations meq/m^3)						
Soil 1 (rock)	69	35	130	55	76	90
Soil 2	69	121	83	133	143	153

Figure 6.—Upper: ANC at West Glacier Lake outlet with wet deposition increasing to 35, 60, and 85 meq/m³ over a 5-year period starting at year zero using final input parameters. Lower: Time course for simulated pH.

Overall, West Glacier is the more sensitive of the two catchments, largely because of the lower initial ANC, and to some extent the lower capacity for exchange buffering. As noted previously, the drop in ANC per unit of increased acid concentration is very similar for the two catchments.

The 30-year results for the initial simulation are included in table 7. Even though the initial and final parameter sets differ in important aspects, the forecast results are generally similar. Lake alkalinity predicted by the initial set (table 7) runs about 4 meq/m³ higher than predicted by the final set. The reason for this difference is that a higher initial weathering on the bare rock results in a greater increase in we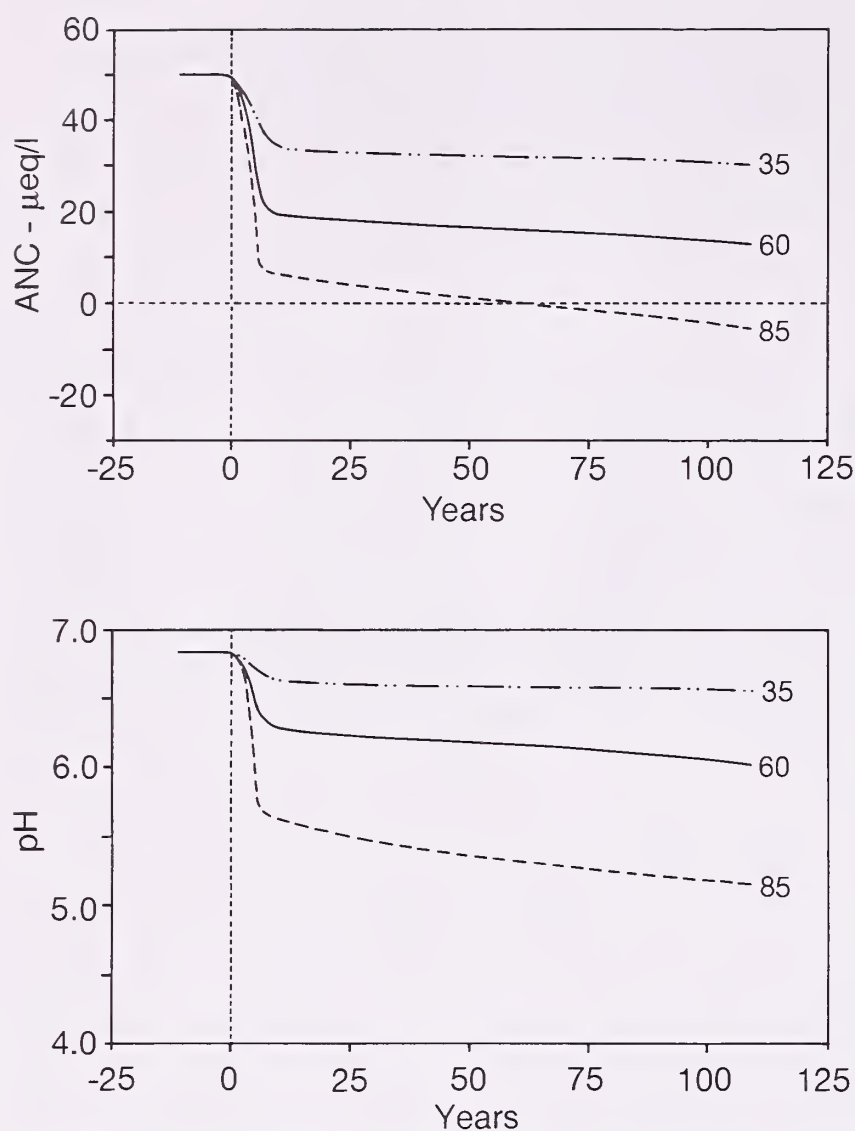athering as H⁺ ion increases. Because the majority of the catchment is bare rock, the overall result is increased release of base cations and a higher final ANC. However, this deviation is within expected error for long-term simulations, and the moderate difference in predictions suggests the conclusions are reasonably robust. As the general pattern of change is quite similar in both cases, no time courses are shown using the initial parameter set.

H⁺ Weathering Exponent

An important assumption in a model of this type is the effect of changes in acidity on the rate of release of base cations through weathering reactions. The usual assumption, as found in the MAGIC model and others such as the model of Schnoor and Stumm (1985), is that weathering is a function of H⁺ concentration such that

$$W = a(H^+)^b$$

where W is the weathering rate and a and b are constants. The exponent b is commonly less than 1.0 so that the increase in weathering is less than the increase in acidity. Such fractional-order rate constants are common in geochemical reactions. Specific information on the appropriate value of b for any specific catchment is seldom available, and common practice is to assume a value of 0.5, i.e., that weathering is a one-half-order reaction with respect to (H⁺).

For the runs reported above, this half-order assumption was used. However, because of its potential importance in determining effects of changes in acid deposition, some runs were also made to examine the effect of changes in the order of this reaction. Selected parameters from simulations using values of 0.3, 0.5, and 0.7 for b are shown in table 8. The results proved to be quite different for the two catchments.

Table 8.—Selected chemical parameters from MAGIC simulations assuming weathering to be proportional to the 0.3, 0.5, and 0.7 power of (H⁺). Precipitation acidity was increased linearly from the present level to pH 4.27 over a 5-year period. Values shown are those predicted 25 years after precipitation acidity reached the final level.

Parameter	Units	Present	Exponent		
			0.3	0.5	0.7
East Glacier Lake					
ANC	meq/m³	49.9	16.8	17.9	17.9
pH		6.8	6.2	6.2	6.2
Soil 1 (rock)					
(H⁺)	meq/m³	3.5	22.8	15.2	11.4
pH		5.5	4.6	4.8	4.9
Weathering	meq/m³	30.9	54.2	64.5	70.9
Soil 2					
(H⁺)	meq/m³	27.9	40.5	40.4	40.3
pH		4.5	4.5	4.4	4.4
Weathering	meq/m³	30.9	38.5	41.3	44.3
Base sat.	%	43.6	41.6	41.8	42.0
West Glacier Lake					
ANC	meq/m³	38.0	−3.3	2.0	6.4
pH		6.7	5.2	5.4	5.7
Soil 1 (rock)					
(H⁺)	meq/m³	5.6	31.6	26.9	22.4
pH		5.2	4.5	4.6	4.7
Weathering	meq/m³	34.7	54.2	76.0	91.2
Soil 2					
(H⁺)	meq/m³	32.1	45.3	44.8	44.3
pH		4.5	4.3	4.3	4.4
Weathering	meq/m³	121.3	134.4	143.3	152.0
Base sat.	%	45.6	41.1	41.7	42.3

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At East Glacier these changes in the order of the weathering-rate reaction made very little difference in the simulated lake chemistry 30 years after precipitation acidity was increased (25 years after precipitation acidity reached the final level). At West Glacier, however, reducing the exponent from 0.5 to 0.3 reduced the simulated lake ANC by 5.3 meq/m^3, while increasing the exponent from 0.5 to 0.7 increased lake ANC by 4.4 meq/m^3. The difference seems to be related to the nature of the catchments.

At East Glacier only 19% of the area is covered by rock and rubbleland (Soil 1). The weathering rate changes significantly in this area as a result of changes in the exponent, but the relative area is small, and the runoff is routed through the true soil where it is subject to exchange buffering. On the true soil (Soil 2), changes in the weathering rate due to differences in the exponent are small, and what increase does take place is again subject to exchange buffering. The net result is that lake chemistry is not much affected by the order of the rate reaction. At West Glacier some 61% of the area is covered by rock and rubbleland. Again, changes in weathering rate due to changes in the assumed reaction order are significant on this rock and rubbleland. Because the area is relatively large and much of the runoff flows directly to the lake, these changes are almost immediately reflected in changes in lake chemistry. While there are some changes in weathering rate in the true soil as a result of changes in the reaction order, this increased weathering is buffered by soil exchange processes and thus has less direct effect on lake chemistry.

The results from these two catchments suggest that the effect of the weathering rate exponent is likely to be much greater for rock and rubbleland than for water passing through soils, or that buffering processes other than base cation release by weathering are likely to determine the relative effect of this parameter. However, this conclusion is based on a very limited number of simulations, and the reliability of such generalization is questionable at present.

SEASONAL SIMULATIONS

Input Parameters

Seasonal simulations were run only for the West Glacier catchment. In this mode some input parameters are required on a monthly basis, while others remain constant over the season. For the most part, those that remain constant are the same as for the final long-term simulations described earlier and may be found in tables 1, 2, and 3. Those parameters that are constant over the season but that differ from the long-term simulation are shown in table 9. The decrease in the maximum SO$_4$ adsorption capacity for Soil 1 was inserted simply to ensure that the model would not simulate any retention of SO$_4$ in the rock and rubbleland. The differences in Ca

weathering, uptake, and lake treatment resulted from the calibration procedure and are explained in this section. Selectivity coefficients are, of course, internally calculated, and the values obtained for the real soil (Soil 2) are close to those in the long-term simulations.

Monthly input values are shown in table 10. Runoff values are taken directly from 3-year observed means (Reuss et al. 1993) and converted to monthly percentages. Precipitation input values are, of course, an estimate of snowmelt input rather than an estimate of when the precipitation actually fell. These were obtained by simply assuming an approximate one week lag between snowmelt and lake outflow; i.e., the monthly input percentages are obtained by moving one-fourth of each month's outflow percentage to the previous month. The most difficult problem was assigning the monthly deposition inputs. Early snowmelt is much more concentrated than later melt water (Bales et al. 1990, Rochette et al. 1988). This is apparent from the monthly relative SO$_4$ con-

Table 9.—Input parameters for the West Glacier seasonal simulations that remain constant over the season. Only those parameters that differ from those used for the long-term simulation are shown. Remaining parameters are the same as those shown for the revised simulations in tables 1, 2, and 3.

Parameter	Lake		Soil 1		Soil 2	
	Long term	seasonal	Long term	seasonal	Long term	seasonal
SO$_4$ Maxcap meq/kg			1.0	0.1		
Ca weathering "			20.0	18.0	70.0	63.0
Ca uptake "			0.0	2.0	0.0	2.0
Ca treatment "	0.0	40.0				
Selection coefficients*						
Log10(KS$_{AlCa}$)			1.50	1.33	1.55	1.39
Log10(KS$_{AlMg}$)			1.54	1.49	1.58	1.79
Log10(KS$_{AlNa}$)			−0.65	−0.65	−0.38	−0.36
Log10(KS$_{AlK}$)			−2.55	−2.35	−2.33	−2.33

*Calculated internally

Table 10.—Seasonal input parameters for the West Glacier simulations.

Month	Runoff	Precip	Deposition	Temp	
				Soil 1	Soil 2
	——— % of Annual ———			——— °C ———	
Jan	0	0	0	2.8	2.8
Feb	0	0	0	2.0	2.0
Mar	0	0	0	2.8	2.8
Apr	0.5	2.1	11.9	5.0	5.0
May	8.2	15.5	42.0	8.0	8.0
Jun	37.0	35.6	25.0	11.0	11.0
Jul	30.4	26.2	9.0	13.2	13.2
Aug	13.3	11.8	5.0	14.0	14.0
Sep	7.1	6.2	4.0	13.2	13.2
Oct	3.4	2.6	3.0	11.0	11.0
Nov	0	0.0	0	8.0	8.0
Dec	0	0.0	0	5.0	5.0

centrations, i.e., the mean monthly concentration divided by the annual volume-weighted mean, as shown in figure 7. The effect is much stronger in the tributary streams than at the lake outlet, probably due to the fact that the lake outlet integrates snowmelt from the various areas of the catchment, and may be influenced by some SO_4 adsorption in the soil. Initial values were derived by plotting the relative concentration against relative flows for the tributary streams and applying the relationship to the previously calculated precipitation inputs. Some adjustment was required to ensure that the monthly deposition percentages (table 10) sum to 100%.

Model Calibrations

There is marked seasonal variation in water chemistry at the West Glacier outlet. If seasonal effects related to changes in deposition are to be simulated,
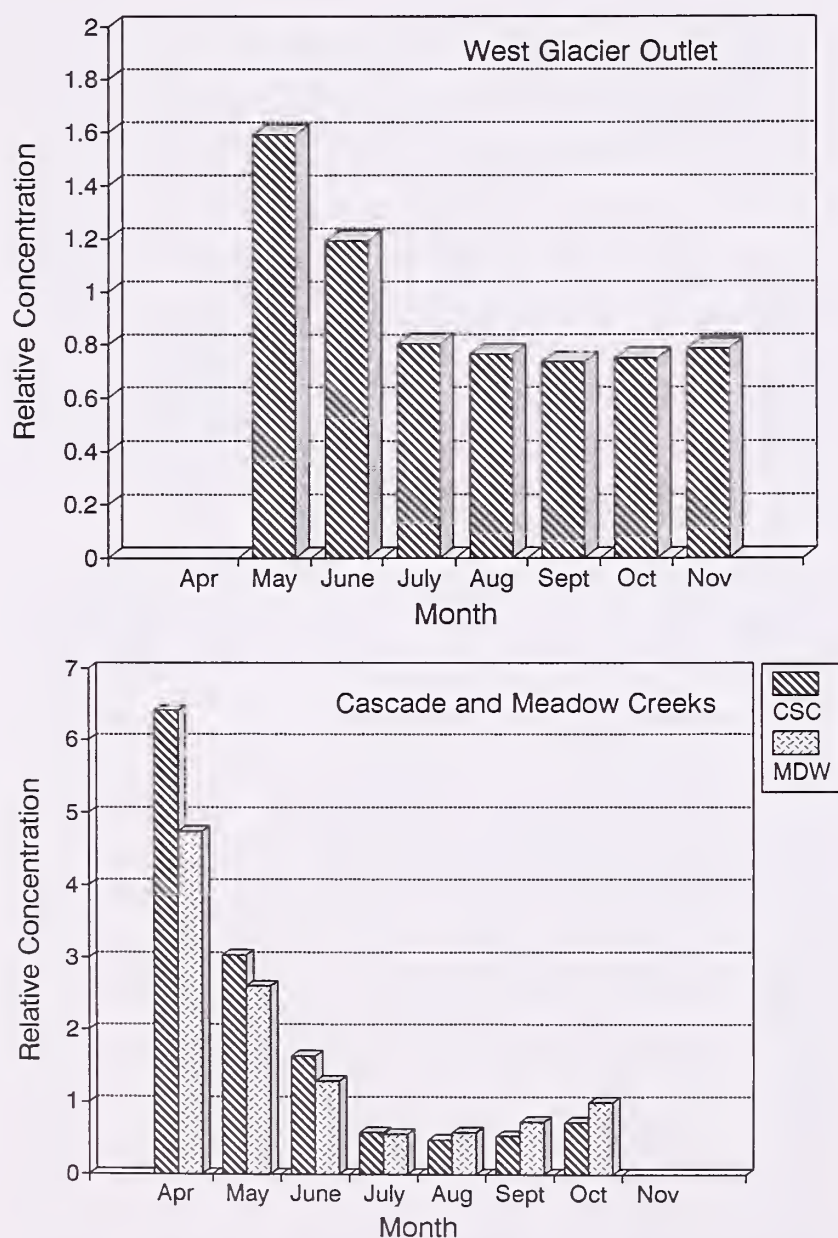
the model must first simulate the current seasonal changes. Seasonal changes in ANC and SO_4 were selected as key parameters. The seasonal SO_4 pattern in the simulation (figure 8) resulted simply from the differential melting implied by the relationship between monthly deposition and precipitation inputs as described in the previous section. While the springtime drop of the simulated values occurs slightly earlier than the observed values, on an overall basis the SO_4 calibration was judged adequate for our purpose so no further adjustments were made during calibration.

High lake ANC values are observed very early in the season, dropping off rapidly when snowmelt occurs (figure 8). Examination of the chemical data reveals that most of this increased ANC is due to an accumulation of base cations in excess of the strong acid anions, rather than a loss of anions by reduction of SO_4 and NO_3. This pattern could be partially simulated simply by the melting/dilution relationship, but the resulting seasonal changes in ANC were less than those actually observed. Manipulation of soil CO_2 had little effect due to the low pH. Apparently, the build-up in base cations during the win-

Figure 7.—Relative SO_4 (mean monthly concentration divided by the annual volume-weighted mean) by months for West Glacier Lake outlet (upper) and the Cascade and Meadow Creek tributaries (lower).
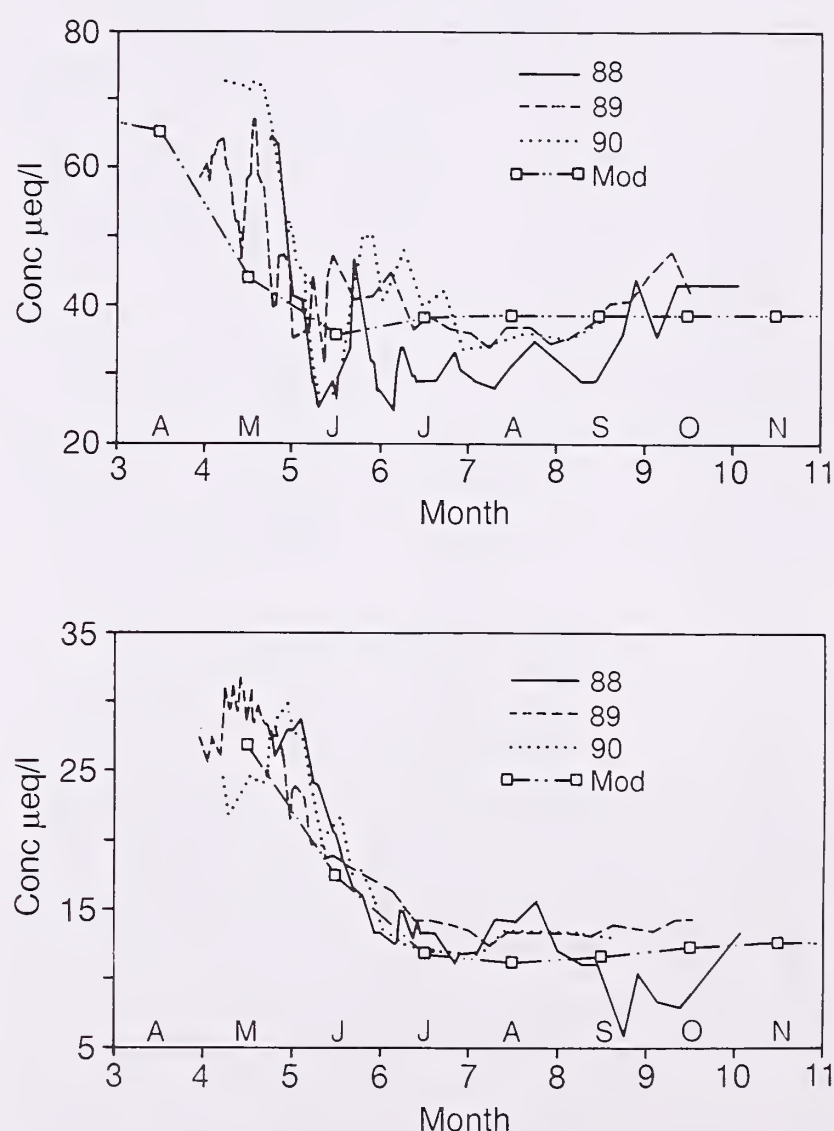

Figure 8.—Seasonal concentrations of ANC (upper) and SO_4 (lower) as observed in 1988, 1989, and 1990 and as simulated by the MAGIC model.

ter while discharge is near zero results from either exchange with the sediments or seepage of a small amount of high alkalinity water from the deep layers. A modeling expedient was adopted that involved simply adding a small amount of Ca (40 meq/m² of lake surface) to the lake during the winter, using the treatment capability in the model. In order to preserve the overall mass balance in the system, an approximately similar amount of Ca was then removed from the soil (2 meq/m² of land surface) via the uptake function in the model. The resulting winter flux simulated in this manner amounts to about 3% of the total annual flux of base cations in the system. The resulting seasonal ANC pattern (figure 8) is generally similar to the observed pattern, although the simulated drop occurs somewhat ahead of the observed drop. This apparently results from the use of monthly mean values to simulate processes that actually occur on a somewhat shorter time scale, so the seasonal calibration pattern as shown in figure 8 was accepted for our purpose.

Finally, when West Glacier Lake was simulated on a seasonal basis, a small difference was found in predicted present-annual-average lake ANC as compared to the above long-term simulations using the same weathering rates. The most likely reason for this discrepancy has to do with the way annual averages are calculated in the model, since these are apparently simply the mean of the monthly values rather than volume-weighted means. Another possibility is that the long-term effects in the model simply turn out somewhat differently when large seasonal fluctuations are simulated. While the differences were not major, for purposes of comparison between long-term and seasonal runs it appeared preferable to adjust the calibration to obtain the same present annual ANC values for the seasonal and long-term runs. This was done by decreasing the Ca weathering by 10% for the seasonal runs (table 9.)

Figure 9.—Seasonal pattern of simulated ANC (upper) and pH (lower) at West Glacier Lake outlet with wet deposition of 35 and 60 meq/m³. Season is 15 years after onset of increased acidity and 10 years after precipitation acidity reaches its maximum level.

Results

Only two forecast scenarios were run for the seasonal simulations, (1) the basic scenario using 60 meq/m³ SO₄ as wet deposition (72 meq/m³ total) and (2) the low scenario of 35 meq/m³ SO₄ wet (42 meq/m³ total). Forecast seasonal patterns for lake ANC and pH 15 years after the onset of the acid deposition (10 years after reaching the maximum level) are shown in figure 9. Clearly, a very marked seasonal effect is forecast with very acidic waters (pH 5.1 and ANC −32 meq/m³) during the snowmelt period for the 60 meq/m³ SO₄ scenario (precipitation pH of 4.27). Al^{3+} is also elevated at this time, exceeding 17 meq/m³. By contrast, 15 years after the onset of the acid deposition, the forecast annual average ANC is 2 meq/m³ and pH is 5.8. One would therefore conclude that damaging seasonal effects would likely be observed well before annual average values reached the unacceptable range.

Seasonal effects are also apparent in the 35 meq/m³ SO₄ scenario (precipitation pH of 4.55). However, the forecast monthly mean ANC of the lake water remains positive throughout the season and pH never drops below 5.9. While such water would likely be acceptable, the actual short-term effects would likely be considerably more severe than indicated by the monthly means. In fact, while the model only preserves monthly means for output, it shows individual excursions of ANC well below zero during snowmelt for this scenario. The results seem to suggest that a precipitation pH in the range of 4.5 to 4.6 would present a considerable danger to the lake ecosystem as it presently exists. Precipitation pH in the 4.2 to 4.3 range would undoubtedly cause severe biological damage. While not included directly in this simulation, tributary streams would be adversely affected at deposition levels well below those that could be tolerated by the lake (Reuss et al. 1993).

DISCUSSION

A model such as the MAGIC model used here is simply a protocol or framework that makes the necessary calculations to apply our current understanding of the processes involved in a consistent manner. While far from perfect, the model takes into account many of the most important interactions and feedbacks in the system in a manner that would be impossible if the principles were applied in an informal way. While the modeling process is sophisticated enough that predictions may be useful, the primary purpose of applying such models is to help the scientist understand how the systems work and to determine which processes are most important in controlling the response of a given system to outside perturbations. Due to the complexity of the interactions, experienced scientists often find the model response to be counter-intuitive. The apparent inconsistency is usually from processes or interactions controlling the response that are not considered by the investigator. In other cases we may find that inappropriate inputs have been used, or occasionally that the model is simply wrong or inadequate and needs to be improved. Thus by careful use of such a model we can often gain insight into the working of the system that is well beyond what is possible by a less structured analysis.

The forecasts made here suggest that the Glacier Lakes would be moderately sensitive to acidic inputs, with West Glacier more sensitive than East Glacier. West Glacier is also likely to be subject to strong seasonal effects if mean precipitation pH drops below 4.5 as a result of sulfuric acid. Nitric acid effects were not examined.

Some important limitations or areas where further work is needed should be noted. First is the question of the hydrogen-ion dependence of weathering. While mineral weathering is commonly considered to be fractional order with respect to H^+, the lack of more definitive information clearly limits our ability to predict response to acidic deposition. The limited amount of sensitivity analysis conducted here suggests that this limitation may be particularly important in situations where a significant amount of weathering occurs on rock and rubbleland. By contrast, buffering processes in soils would tend to decrease the sensitivity to this parameter. Unfortunately, there is a good deal of speculation involved in any such evaluation. Further research, including field, laboratory, and model studies, will be required to clarify this most difficult issue.

Another area that requires better understanding is the acceptable range of selection coefficients, particularly those for Ca-Al and Mg-Al exchange. Calibration of the model may be quite different if these are tightly constrained by the operator as compared to a calibration where they are allowed to vary without constraint. In general, low values imply that exchangeable bases are very tightly held, so acidification of surface water can occur while base saturation is relatively high. High values imply that exchangeable bases must be highly depleted before leachates will be acidified. Further information as to appropriate ranges for various types of soil is clearly needed. Again, model studies to further clarify the implications of allowing these to vary would be useful.

On a broader perspective, we must remember that the MAGIC model uses a lumped parameter approach. It can accommodate at most two soils, arranged either vertically or side by side. Thus, soils that are quite varied in chemical characteristics, both in depth and across the catchment, must be aggregated in such a way that they are described by a single set of chemical parameters. A crucial question arises as to what extent this aggregation affects the model results. Indeed, the fundamental question is whether or not the general equations that describe the processes can be validly applied to the aggregated system. One approach to this problem is to do further model studies, either with the MAGIC model or models that describe the soil processes in a similar way, to determine to what degree the response of a group of systems can be described by a lumped parameter approach. The alternative to the lumped parameter approach is to build a model that would accommodate a great number of soils, arranged both vertically and horizontally. In practice this approach runs into serious problems due to the difficulty of describing the chemical properties on this scale; and more importantly, it is very difficult to describe the hydrological flow and transfer of materials in such a model. The uncertainties in this process would likely be at least as great as those involved in the lumped parameter approach. Even if done successfully for any particular catchment, it would be very difficult to transfer the model to other catchments.

CONCLUSIONS

1. Model studies indicate that, in general, the soils in the Glacier Lakes catchments must be substantially undersaturated with respect to gibbsite-type minerals, and that the negative charge in the soil solutions must be largely organic in nature.

2. East Glacier Lake would be only moderately sensitive to acidification induced by sulfuric acid. Model-derived estimates suggest that annual average ANC would not drop below 0 unless precipitation pH falls below 4.3. Only precipitation acidity induced by sulfuric acid was considered. Possible seasonal effects were not investigated for East Glacier. Model estimates of the Henriksen F factor for East Glacier are approximately 0.65.

3. West Glacier is more sensitive than East Glacier. Average annual lake ANC would reach 0 at an input pH of about 4.3. However, seasonal effects would be severe at this level. The lake itself could perhaps tolerate a precipitation pH of 4.5–4.6. Seasonal ef-

fects on less than a monthly scale cannot be simulated and may become a problem at this pH, and tributary streams would undoubtedly become acidic during snowmelt. Model estimates of the Henriksen F factor are near 0.5.

4. Model studies are subject to substantial limitations. Among the major limitations encountered here are the lack of good information on the hydrogen-ion dependence of weathering, the acceptable range for selection (exchange) coefficients, and the general validity of the lumped parameter approach.

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Introduction

The primary source of the soils data for parameterization of the MAGIC model is the report of the Soils Survey prepared by Hopper and Walthall (1987). This survey can be described as semidetailed, meeting or exceeding the criteria for a standard second-order survey, with a level of detail that is close to that found in many third-order surveys. Thirteen mapping units were defined, described, and delineated on a map. Representative pedons were sampled for analysis, and the analytical results from 15 pedons were used in this aggregation.

The MAGIC model is limited to two soils. These may lie one above the other, or adjacent. If more than one soil is used, it is necessary to define the hydrological pathway in terms of the fraction of water that enters each soil, the fraction that moves from one soil to the other, the fraction that moves from each soil to the surface water, etc. However, a brief examination of the soil map shows a complex mosaic of soils for which such a definition of the hydrological pathway is probably impractical. Therefore, the initial parameterization will require an aggregation of the analytical data such that all soils and horizons are combined to provide a single set of chemical parameters.

Procedure

This procedure requires aggregation in both the vertical and horizontal planes. It is difficult and there is probably no satisfactory procedure. The overall principle followed was that the final values should provide a reasonably accurate representation of the total number of negative charges on the cation exchange complex in the two catchments, and of the distribution of cations on these charges. The actual procedures used are explained below.

Map Unit Areas

Soils map overlays were combined with a standard map of the catchments using a computerized mapping system. The area of each subunit delineated on the soils map was then determined and entered into a spreadsheet. Areas were then summed by map unit and catchment (table A-1). For East Glacier, the total area of 26.09 ha plus a lake area of 2.88 ha is consistent with a total catchment area of 29 ha. For West Glacier the total map unit area of 50.82 ha plus a lake area of 3.29 ha falls about 7 ha short of the catchment area of 61 ha. This discrepancy arises because the delineation of the catchment area on the northwest boundary of the soils map is somewhat different from that which was later adopted for the standard map.

Table A-1.—Soil map unit areas for East and West Glacier catchments.

East Glacier map units summary by area			West Glacier map units summary by area		
Map unit	Mafic (m)	Area ha	Map unit	Mafic (m)	Area ha
1		2.38	1		2.87
2		2.77	2		0.69
3		3.03	3		0.65
4		1.54	4		1.01
5		1.97	5		5.04
5	m	2.63	5	m	2.56
6		3.04	6		1.76
7		4.84	7		10.32
7	m	3.71	7	m	3.35
9		0.18	8		0.22
9			9		0.70
		26.09	10		12.18
			11		7.05
			13		2.41
					50.81

The area in question is largely rock outcrop and rubbleland and will be included in that category for purposes of the MAGIC model.

Mineral Soils

Some of the pedons contained organic layers, while others did not. Because the bulk densities of the organic and mineral layers are very different, the organic and mineral layers were kept separate until the final step in the aggregation. The steps followed in the aggregation of the mineral soils were:

1. The analyses of the mineral horizons were aggregated over depth. This was done by multiplying the meq/100 g (or % in the case of carbon) of each component times the depth. These products are then summed and the sum divided by the total depth to get an aggregate (meq/100g) for the profile.

2. The next step was to aggregate similar soils to the extent that chemical properties are reasonably similar. Most map units are complexes composed of at least two subunits. After aggregating the individual pedons, those pedons that represent each subunit were aggregated using a method similar to that above. First the profile depth is multiplied by the previously aggregated meq/100 g. Then the products are summed and again divided by the sum of the depths to get an aggregated meq/100 g for the map units.

Aggregated values of chemical data were calculated for:

— The Typic Cryoboralfs, Pedons WYGL001, 002, 005, and 016. These are used in Map Units 1 and 2.

— Dystric Cryochrepts, Pedons WYGL003, 006, 007, and 015. This aggregation was used for all map subunits classified as Dystric Cryochrepts except in Map Units 5m, 7m, and 13. There is some ambigu-

ity in the use of this aggregate. The soil survey report (Hopper and Walthall 1987) suggests that one, two, or three of the above soils are typical of the Dystric Cryochrepts in individual map units. However, from the chemical data it appears more appropriate that they be lumped and used for all Dystric Cryochrepts except those in the areas of mafic intrusions and the high alpine areas. This aggregate was also used to represent the Lithic Cryochrepts, with appropriate depth adjustment.

Pedons WYGL012 and 014 are also classed as Dystric Cryochrepts. These seem to be special cases. Pedon WYGL012 represents the Dystric Cryochrepts found in areas with substantial mafic intrusions, and while the base saturation (fraction) is about the same as the other profiles, the CEC is significantly higher. Therefore, WYGL012 is used alone for the Dystric Cryochrepts in the mafic map units (5m and 7m). Pedon WYGL014 is from a Dystric Cryochrept in the high alpine area, and is quite different from the others in that the base saturation is much lower. WYGL014 is therefore used alone for map unit 13.

— Typic Cryorthents are represented by pedons WYGL004 and 008, and are found in Map Unit 12.

— Typic Cryumbrepts are represented by profiles WYGL009 and 010. These were aggregated and used for Map Units 6 and 13, with adjustments for depth as needed.

— The Cryaquepts are found in Map Unit 8 and are represented by pedon WYGL011.

The following summarizes the way in which the chemical data is applied to the overall aggregation by map unit.

Aggregate	Pedons (WYGL)		Map Unit
1	1, 2, 5, 16	Typic Cryoboralfs	1, 2
2	3, 6, 7, 15	Dystric Cryochrepts	2, 3, 4, 5, 6, 7
3	4, 8	Typic Cryorthents	12
4	9, 10	Typic Cryumbrepts	6, 13
5	12	Dystric Cryochrept (mafic)	5m, 7m
6	14	Dystric Cryochrept (alpine)	13
7	11	Cryaquepts	8

At this point we have a weighted mean chemical composition for each of the seven aggregate numbers (some of which are single pedons) shown above. These compositions are shown in table A-2.

The next task was to calculate the total volume represented by each of the above aggregations in each of the two catchments (tables A-3a and A-3b). The soil survey report includes an estimate of the rela-

Table A-2.—Summary of depth-weighted means of chemical parameters by aggregation number.

Agg #	Pedon	DEPTH	Ca	Mg	Na	K	AL	H+	ACID	CEC
		cm				meq/100g				
MINERAL										
1	1 2 5 16	102	0.51	0.26	0.02	0.05	4.33	1.50	5.83	6.68
2	3 6 7 15	97.5	2.21	0.54	0.03	0.06	2.57	0.64	3.22	6.06
3	4 8	100.5	4.04	0.97	0.02	0.25	1.44	0.78	2.22	7.51
4	9 10	100.5	0.88	0.18	0.07	0.04	3.79	1.04	4.83	6.00
5	12	102	12.18	5.88	0.02	0.07	16.20	2.68	18.88	37.02
6	14	74	0.834	0.147	0.033	0.050	7.422	1.809	9.231	10.295
7	11	95	3.779	0.931	0.048	0.093	4.603	1.527	6.130	10.980
ORGANIC										
1o	1 2 5 16	2.75	34.62	2.78	0.10	0.62	0.65	0.62	1.27	39.40
2o	7	4	39.25	3.58	0.03	0.45	0.01	0.31	0.32	43.63
3o	None									
4o	None									
5o	12	4	30.30	3.07	2.00	0.46	0.04	0.31	0.35	36.18
6o	14	5	13.37	2.49	0.21	0.52	3.31	1.7	5.01	21.6
7o	None	.								

tive amounts of each soil in a particular map unit, so the area within each map unit represented by each of the above aggregations could be calculated. Depth estimates were taken from the pedon analysis data, but in some cases were modified by depths given in the survey report for a particular soil in a mapping unit depth or the soil notes. Thus, given area and depths, the volume of soil represented by each of the aggregations can be calculated. In most cases, the area estimates of the described soils in each mapping unit added up to only 90% of the area, due to minor inclusions of other soils (or rock land) that are too small to delineate on the map. For our purposes the areas were proportionally adjusted upward so that they totaled 100%, on the assumption that these inclusions would balance out over the catchment.

Many of the soils are described in the report as being stony, extremely stony, gravelly, cobbly, etc. Unfortunately we do not have any measurement of the stone volume, so estimates were made.

For each soil and mapping unit, the description in the survey report that concerns the stoniness was abstracted (table A-4). A volume percentage of stones was estimated based on this description; most of these estimates are in the range of 40-55%. For purposes of our calculations the estimate was applied to depth; i.e., if the stone volume was estimated as 50%, the depths were reduced by half when the final soil volumes were calculated (tables A-3a and A-3b). It is recognized that these adjustments are subjective and may represent a substantial source of error. The calculations are set up in a spreadsheet in such a way that revised estimates can be entered and all recalculation will take place automatically.

Once the total volume of each soil aggregate was estimated, the chemical parameters were aggregated by weighting by the fraction of the total soil volume represented by that soil aggregate in each catchment

Table A-3a.—Calculation of soil volumes and weighted mean chemistry for aggregations of mineral soils in the East Glacier catchment.

A. VOLUME SUMMARY, EAST GLACIER MINERAL SOILS

Map AGG #	Map Unit	Unit Area	Agg (Adj)	Area	Depth	Stones	Volume
		ha	%	ha	m	%	m³ (x10³)
1	1	2.378	65.00	1.546	1.02	50	7.883
1	2	2.768	75.00	2.076	1.02	50	10.588
1	2	2.768	25.00	0.692	1.02	40	4.235
2	1	2.378	35.00	0.832	0.975	55	3.652
2	3	3.03	61.11	1.852	0.400	55	5.000
2	3	3.03	38.89	1.178	0.400	55	2.121
2	4	1.543	66.67	1.029	0.975	40	6.018
2	4	1.543	33.33	0.514	0.975	55	2.257
2	5	1.97	66.67	1.313	0.975	55	5.762
2	6	3.04	33.33	1.013	0.975	55	4.446
2	7	4.843	33.33	1.614	0.975	55	7.083
2	7	4.843	27.78	1.345	0.400	55	2.422
4	6	3.04	66.67	2.027	1.05	55	9.576
5	5m	2.63	66.67	1.753	1.02	55	8.048
5	7m	3.71	33.33	1.237	1.02	55	5.676
5	7m	3.71	27.78	1.031	0.40	55	1.855

B. VOLUME BY AGGREGATION NUMBER, ADJUSTED FOR STONES

Aggregation Number	Area	Volume	Fraction
	ha	m³(x10³)	
1	4.31	22.706	0.262
2	10.69	38.759	0.447
4	2.03	9.576	0.111
5	4.02	5.579	0.180
TOTAL	21.05	6.620	1.000

C. OVERALL WEIGHTED MEAN CHEMISTRY FOR MINERAL SOILS

Ca	Mg	Na	K	Al	H⁺	Total Acid	CEC	Org C
			meq/100g					%
3.413	1.387	0.030	0.056	5.619	1.279	6.898	11.786	0.933

Table A-3b.—Calculation of soil volumes and weighted mean chemistry for aggregations of mineral soils in the West Glacier catchment.

A. VOLUME SUMMARY, WEST GLACIER MINERAL SOILS

Map AGG #	Map Unit	Unit Area	Agg (Adj)	Area	Depth	Stones	Volume
		ha	%	ha	m	%	m³ (x10³)
1	1	2.871	65.00	1.866	1.02	50	9.517
1	2	0.692	75.00	0.519	1.02	50	2.647
1	2	0.692	25.00	0.173	1.02	40	1.059
2	1	2.871	35.00	1.005	0.975	55	4.409
2	3	0.646	61.11	0.395	0.6	55	1.066
2	3	0.646	38.89	0.251	0.4	55	0.452
2	4	1.006	66.67	0.671	0.975	40	3.923
2	4	1.006	33.33	0.335	0.975	55	1.471
2	5	5.045	66.67	3.363	0.975	55	14.755
2	6	1.76	33.33	0.587	0.975	55	2.574
2	7	10.324	33.33	3.441	0.975	55	15.099
2	7	10.324	27.78	2.868	0.4	55	5.162
4	6	1.76	66.67	1.173	1.05	55	5.544
4	13	2.41	33.33	0.803	0.4	55	1.446
5	5m	2.564	66.67	1.709	1.02	55	7.846
5	7m	3.349	33.33	1.116	1.02	55	5.124
5	7m	3.349	27.78	0.930	0.4	55	1.675
6	13	2.41	44.44	1.071	0.74	55	3.567
7	8	0.22	100	0.224	0.95	10	1.911

B. VOLUME BY AGGREGATION NUMBER, ADJUSTED FOR STONES

Aggregation Number	Area	Volume	Fraction
	ha	m³(x10³)	
1	2.558	13.223	0.148
2	12.916	48.912	0.548
4	1.977	6.990	0.078
5	3.756	14.644	0.164
6	1.071	3.567	0.040
7	0.224	1.911	0.021
TOTAL	22.501	89.247	1.000

C. OVERALL WEIGHTED MEAN CHEMISTRY FOR MINERAL SOILS

Ca	Mg	Na	K	Al	H⁺	Total Acid	CEC	Org C
			meq/100g					%
3.471	1.339	0.031	0.059	5.402	1.202	6.603	11.504	1.053

(tables A-3a and A-3b). These estimates are all on a weight basis (i.e., meq/100 g) and include the implicit assumption that if the stones were removed, all mineral soils would have a similar bulk density.

Organic Soils

Aggegation of the organic layers was done separately from the mineral layers, but was carried out in essentially the same fashion. Weighted mean chemistry was calculated for those aggregates that have organic layers (table A-2). Weighted mean chemistry was then calculated for the organic layers for each catchment based on depth and area of each aggregate that has an organic layer (tables A-5a and A-5b). No adjustment for stoniness was applied to the organic layer. The final chemistry of the organic layers was calculated by weighting by the volume of each aggregate, as was done for the mineral soils.

Table A-4.—Soil mapping units, including notes on stoniness, presence of litter, and applicable profile and aggregate numbers.

MAP UNIT	COMPONENT	STONINESS	STONE ADJ	LITTER	AREA %	PROFILE # %	AGG #
1	Typic Cryoboralfs	Very gravelly, extremely gravelly, extremely cobbly	50	Y	65	1,2,5,16	1
	Dystric Cryochrepts	Some areas very or extremely cobbly, cobbly, bouldery, gravelly	55	Y	35	3,6,7,15	2
2	Typic Cryoboralfs	Very stony	55	N	75	1,2,5,16	1
		Stony	40	Y	25	1,2,5,16	1
3	Dystric Cryochrepts	Extremely gravelly or extremely stony, bedrock ca 60 cm	55	N	55	3,6,7,15	2
	Lithic Cryochrepts	Similar but bedrock <50 cm	55	N	35	3,6,7,15	2
4	Dystric Cryochrepts	Stony, subsoil extremely gravelly	40	Y	60	3,6,7,15	2
		Very stony (extremely cobbly)	55	N	30	3,6,7,15	2
5	Dystric Cryochrepts	Extremely cobbly, gravelly	55	N	60	3,6,7,15	2
	Rubbleland (talus)				30		
5m	Dystric Cryochrepts (mafic)	Same as MU 5 above	55	N	60	12	5
	Rubbleland				30		
6	Typic Cryumbrepts	Loam (21 cm) over very stony and extremely cobbly substratum	40	N	60	9,10	4
	Dystric Cryochrepts	Extremely cobbly	55	N	30	3,6,7,15	2
7	Rock Outcrop				35	NA	
	Dystric Cryochrepts	Gravelly, very gravelly to extremely cobbly	55	Y	30	3,6,7,15	2
	Lithic Cryochrepts	Similar to above but <50 cm	55	Y	25	3,6,7,15	2
7m	Rock Outcrop (mafic intrusives)				35	NA	
	Dystric Cryochrepts	Similar to MU 7 above	55	Y	30	12	5
	Lithic Cryochrepts	Similar to MU 7 above	55	Y	25	12	5
8	Histic Cryaquepts	No mention of stones	10	N	50	11	7
	Aeric Cryaquepts	No mention of stones	10	N	40	11	7
9	Rubbleland (level to moderate)				90	NA	
10	Rubbleland (steep)				55	NA	
	Rock Outcrop				40	NA	
11	Snowfields						
12	Typic Cryorthents	Extremely gravelly, extremely stony	55	N	55	4,8	3
	Rubbleland				40		
13	Dystric Cryochrepts	Extremely stony	55	Y	40	14	6
	Lithic Cryumbrepts	Extremely stony, depth <50 cm	55	Y	30	9,10	4
	Rock Outcrop				20	NA	

At this point a volume and a weighted mean chemistry value was available for both the mineral and organic layers for each catchment. As these chemical values are on a weight basis, it was necessary to estimate bulk densities in order to combine the organic and mineral soil values. Bulk densities for mineral soils (on a stone-free basis) were taken as 1.25, while the bulk density of the organic layer was estimated as 0.35. Chemical parameters for the combined organic and mineral values were taken by weighting the means of the organic and mineral fractions by the total weight (table A-6). Saturation values for the base cations were calculated from the mean exchangeable bases (meq/100g) and the mean CEC. Mean soil depth was calculated by dividing total volume by total areas of soil in each catchment, excluding rock, rubbleland, and snowfields. Mean bulk densities were calculated by dividing total soil mass by total volume.

Table A-5a.—Calculation of soil volumes and weighted mean chemistry for soil organic layers in the East Glacier catchment.

A. VOLUME SUMMARY, EAST GLACIER ORGANIC SOILS

Map AGG #	Map Unit	Map Unit Area	Agg (Adj)	Area	Depth	Stones	Volume
		ha	%	ha	m	%	m³ (x10³)
1	1	2.378	65.00	1.546	0.0275	0	0.425
1	2	2.768					0.000
1	2	2.768	25.00	0.692	0.0275	0	0.190
2	1	2.378	35.00	0.832	0.04	0	0.333
2	3	3.03					0.000
2	3	3.03					0.000
2	4	1.543	66.67	1.029	0.04	0	0.411
2	4	1.543					0.000
2	5	1.97					0.000
2	6	3.04					0.000
2	7	4.843	33.33	1.614	0.04	0	0.646
2	7	4.843	27.78	1.345	0.04	0	0.538
5	5m	2.63		0.000			0.000
5	7m	3.71	33.33	1.237	0.04	0	0.495
5	7m	3.71	27.78	1.031	0.04	0	0.412

B. VOLUME BY AGGREGATION NUMBER, ADJUSTED FOR STONES

Aggregation Number	Area	Volume	Fraction
	ha	m³(x10³)	
1	2.238	0.615	0.178
2	4.821	1.928	0.559
5	2.267	0.907	0.263
TOTAL	9.326	3.450	1.000

C. OVERALL WEIGHTED MEAN CHEMISTRY FOR MINERAL SOILS

Ca	Mg	Na	K	Al	H+	Total Acid	CEC	Org C
meq/100g								%
36.072	3.304	0.560	0.483	0.129	0.366	0.495	40.915	22.423

Table A-5b.—Calculation of soil volumes and weighted mean chemistry for soil organic layers in the West Glacier catchment.

A. VOLUME SUMMARY, WEST GLACIER ORGANIC SOILS

AGG #	Map Unit	Map Unit Area	Agg (Adj)	Area	Depth	Stones	Volume
		ha	%	ha	m	%	m³ (x10³)
1	1	2.871	65.00	1.866	0.0275	0	0.513
1	2	0.692					0.000
1	2	0.692	25.00	0.173	0.0275	0	0.048
2	1	2.871	35.00	1.005	0.04	0	0.402
2	3	0.646					0.000
2	3	0.646					0.000
2	4	1.006	66.67	0.671	0.04	0	0.268
2	4	1.006					0.000
2	5	5.045					0.000
2	6	1.76					0.000
2	7	10.324	33.33	3.441	0.04	0	1.377
2	7	10.324	27.78	2.868	0.04	0	1.147
5	5m	2.564		0.000			0.000
5	7m	3.349	33.33	1.116	0.04	0	0.447
5	7m	3.349	27.78	0.930	0.04	0	0.372
6	13	2.41	44.44	1.071	0.05	0	0.536

B. VOLUME BY AGGREGATION NUMBER, ADJUSTED FOR STONES

Aggregation Number	Area	Volume	Fraction
	ha	m³(x10³)	
1	2.039	0.561	0.110
2	7.985	3.194	0.625
5	2.047	0.819	0.160
6	1.071	0.536	0.105
TOTAL	13.142	5.109	1.000

C. OVERALL WEIGHTED MEAN CHEMISTRY FOR MINERAL SOILS

Ca	Mg	Na	K	Al	H+	Total Acid	CEC	Org C
meq/100g								%
34.595	3.297	0.372	0.478	0.428	0.490	0.918	39.659	22.692

Table A-6.—Combined organic and mineral soil chemical
parameter estimates.

EAST GLACIER

SOIL	BULK DENSITY	WEIGHT tons (x10^3)	WEIGHTING FACTORS
Organic	0.35	1.208	0.0110
Mineral	1.25	108.275	0.9890
Total	109.4827	1.0000	

Mean BD
(tot wt/tot vol) = 1.2155

Mean Depth
(tot vol)/area = 0.4278 m

Ca	Mg	Na	K	Al	H$^+$	ACID	CEC	ORG C
			meq/100g					%
3.773	1.408	0.036	0.061	5.559	1.269	6.827	12.107	1.170

————————————— % Saturation —————————————

Ca	Mg	Na	K	Al	H$^+$	ACID
31.168	11.632	0.296	0.505	45.912	10.480	56.392

WEST GLACIER

SOIL	BULK DENSITY	WEIGHT tons (x10^3)	WEIGHTING FACTORS
Organic	0.35	1.788	0.0162
Mineral	1.25	108.275	0.9838
Total	110.0631	1.0000	

Mean BD
(tot wt/tot vol) = 1.1665

Mean Depth
(tot vol)/area = 0.4193 m

Ca	Mg	Na	K	Al	H$^+$	ACID	CEC	ORG C
			meq/100g					%
3.977	1.371	0.037	0.065	5.321	1.190	6.511	11.961	1.036

————————————— % Saturation —————————————

Ca	Mg	Na	K	Al	H$^+$	ACID
33.248	11.461	0.305	0.547	44.485	9.949	54.434

Rocky Mountain Station

Station lab locations:

Albuquerque, NM
Flagstaff, AZ
Fort Collins, CO*
Laramie, WY
Lincoln, NE
Rapid City, SD

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